Operation Of Project X Linac As A Driver For Muon Collider

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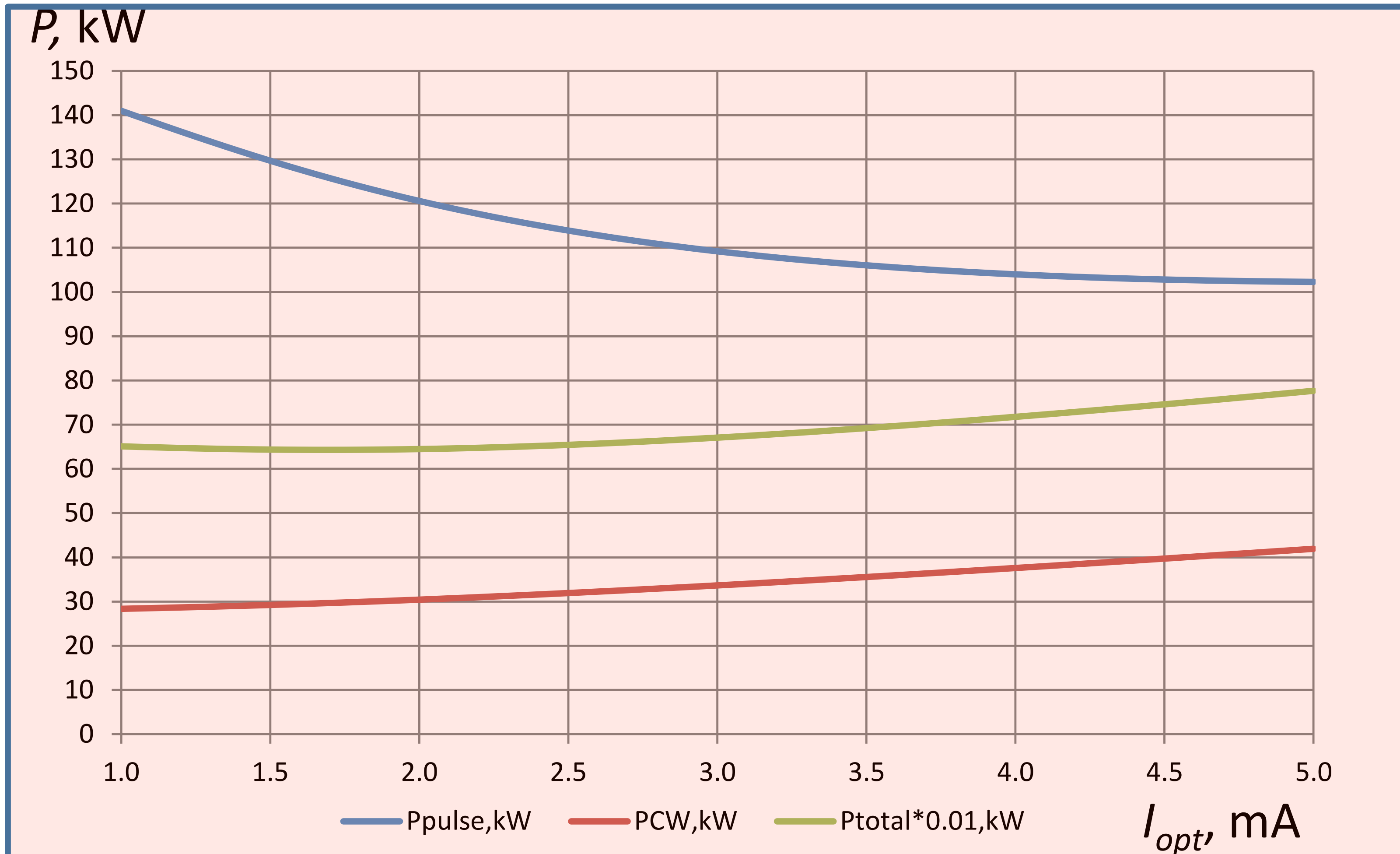
Fermilab TD and AD

Motivation and Outline

- Baseline Project X design is well established
  - CW operation with 1 mA average current at 3 GeV; pulsed 3-8 GeV
- Project X is considered as a beam source for a future Neutrino Factory and/or Muon Collider
  - 15 Hz pulses of 6.7 ms with 5 mA average and 10 mA peak current
    - 3-4 MW at 8 GeV
- In this study we address issues associated with operation of Project X linac (specifically, HE 650 MHz section) as a driver for Muon Collider
  - Coupling optimization
  - Incoherent losses
  - Resonance excitation of HOMs
    - cryogenic losses
    - emittance increase
  - Collective effects

Coupler Optimization

f = 650 MHz
δf = 18 Hz - microphonics
(R/Q) = 640 Ohm
I_{CW} = 1 mA - DC current
I_{pulse} = 5 mA - pulse current
φ = -10° - synch. phase
V = 17.5 MV - gain/cavity
τ = 6.7 ms - pulse width
f_{rep} = 15 Hz - rep. rate
N = 160 - number of cavities
16% overhead



I_{opt} is the current which corresponds to the optimal coupling.

Q_{load}(1mA) = 1.5e7
Q_{load}(2mA) = 1.1e7
P_{CW}(1mA) = 28 kW
P_{CW}(2mA) = 30 kW

$$P_{total} = N(P_{CW}(1-f_{rep}\,\tau) + P_{pulse}\,f_{rep}\,\tau)$$

- Total power is minimal if coupler is optimized for 2 mA. RF source should provide power of 120 kW in 10% duty cycle
- It is possible to use coupling for 2 mA; it will take 7% more power for the period before MC
- Better to use coupling tuned for 1 mA and adjust coupling when MC is built

Incoherent Losses

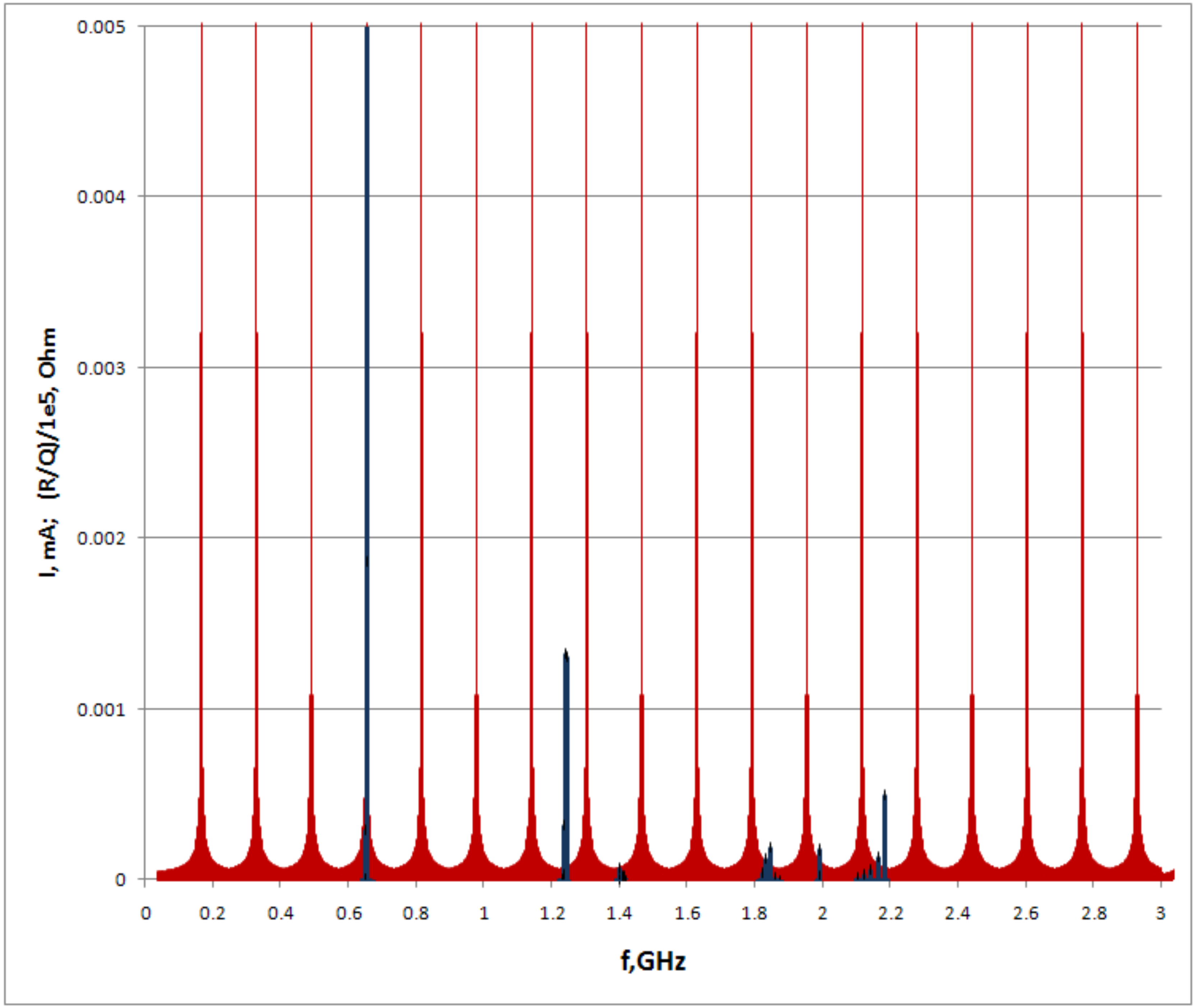
- MC pulses (5mA average current, 10% DF, 10mA peak curent)
  - Average current increases by factor of 1.4
  - Incoherent losses increase 1.9 times

	ProjectX	SNS	ILC
I_{av}, mA	1(PX)/1.4(PX+MC)	1	4.80E-02
Q_b, pC	25.6(PX)/51.2(MC)	58	3200
k_{loss}, V/pC	2	1.1	13.4
P_{av}, mW/cavity	51(PX)/97(PX+MC)	64	2065

- Incoherent losses are small

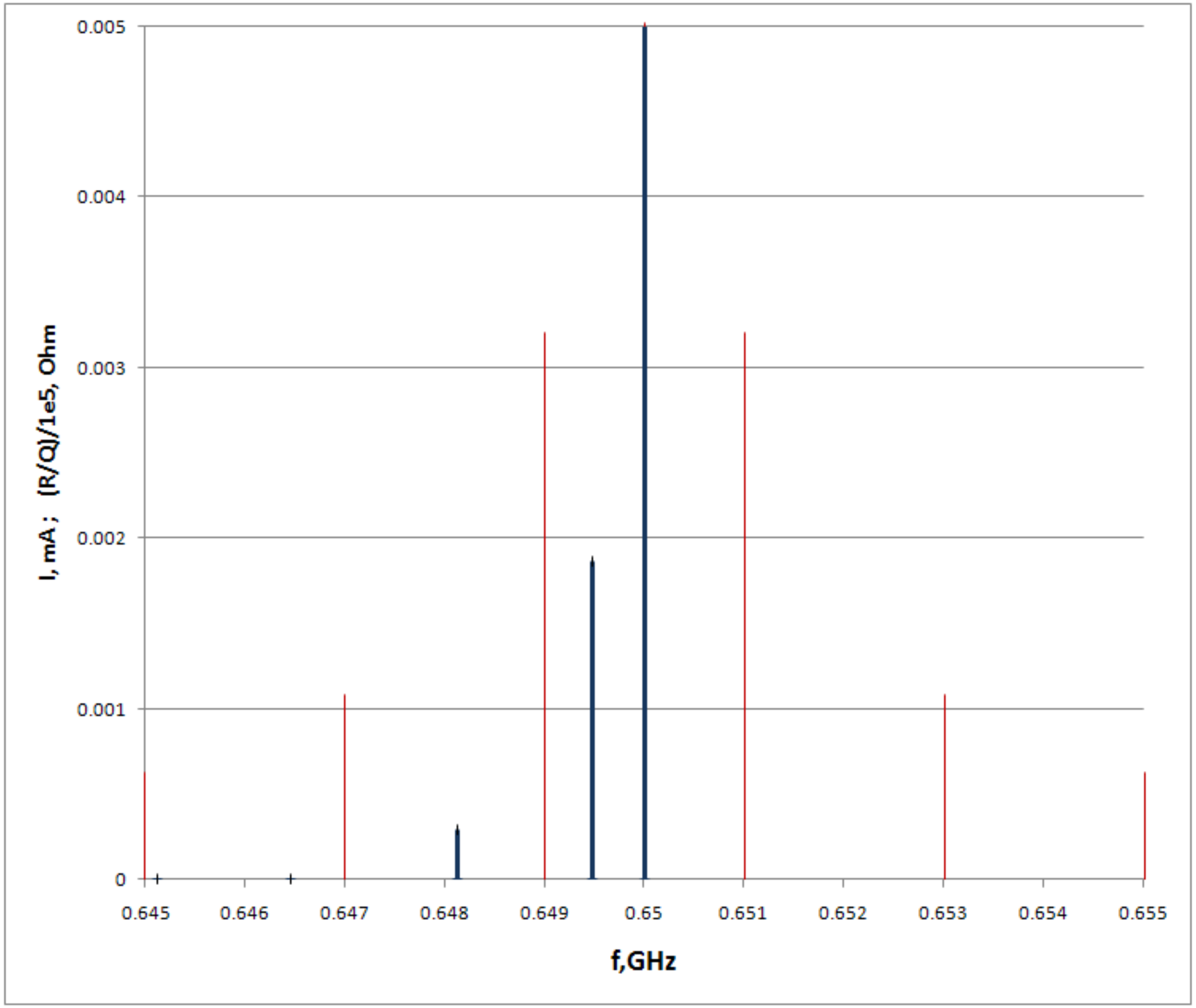
Beam and HOMs spectra

- Idealized beam spectrum: 1us period, 50% DF
- HE 650 MHz cavity impedance



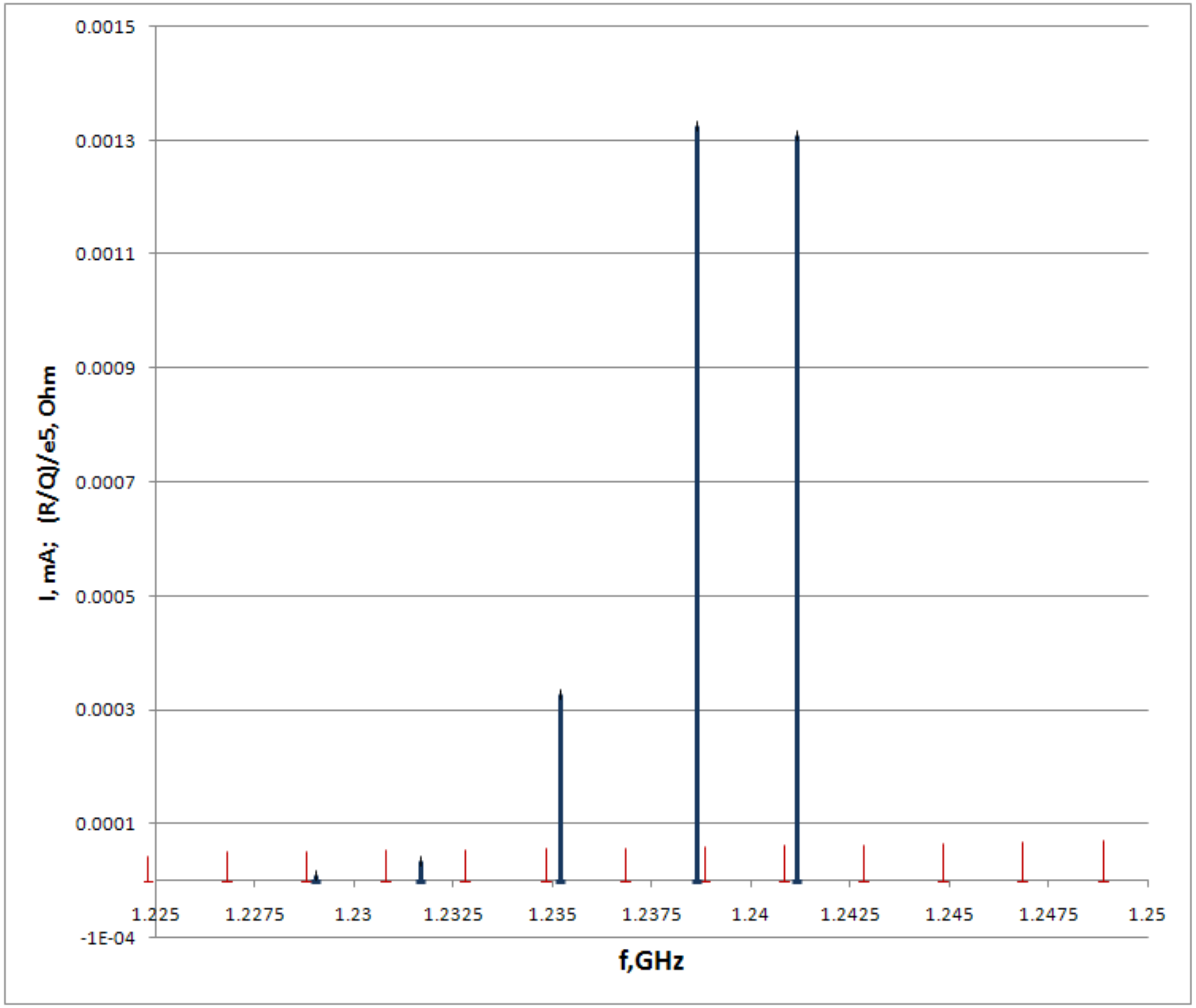
- Strong cavity resonances fall between main beam spectrum lines; HOM frequency spread ~1MHz

1st Passband (Operating)



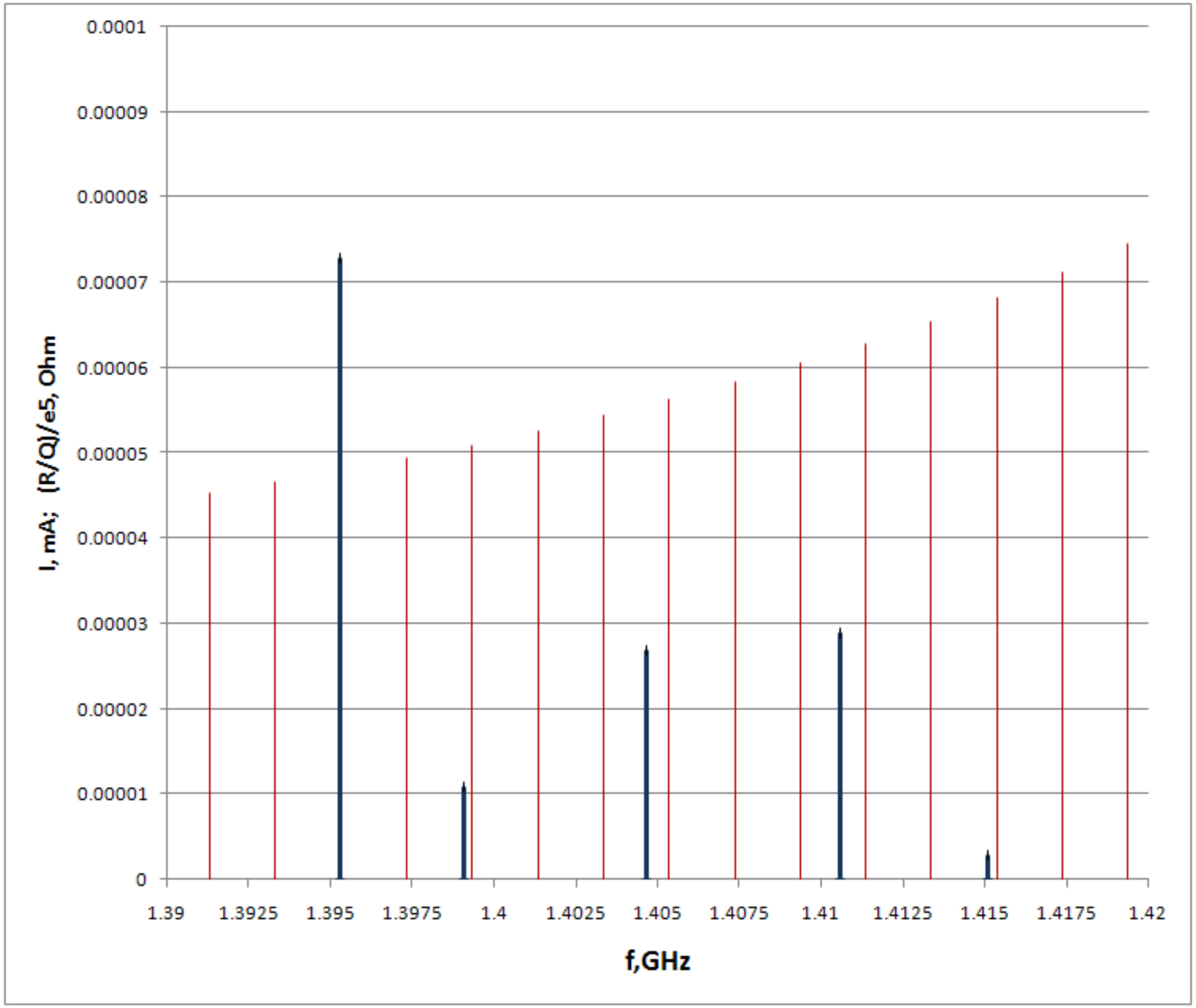
- 4th mode falls between operating frequency and a side band frequency. This mode is strongly coupled to the main coupler

2nd Passband



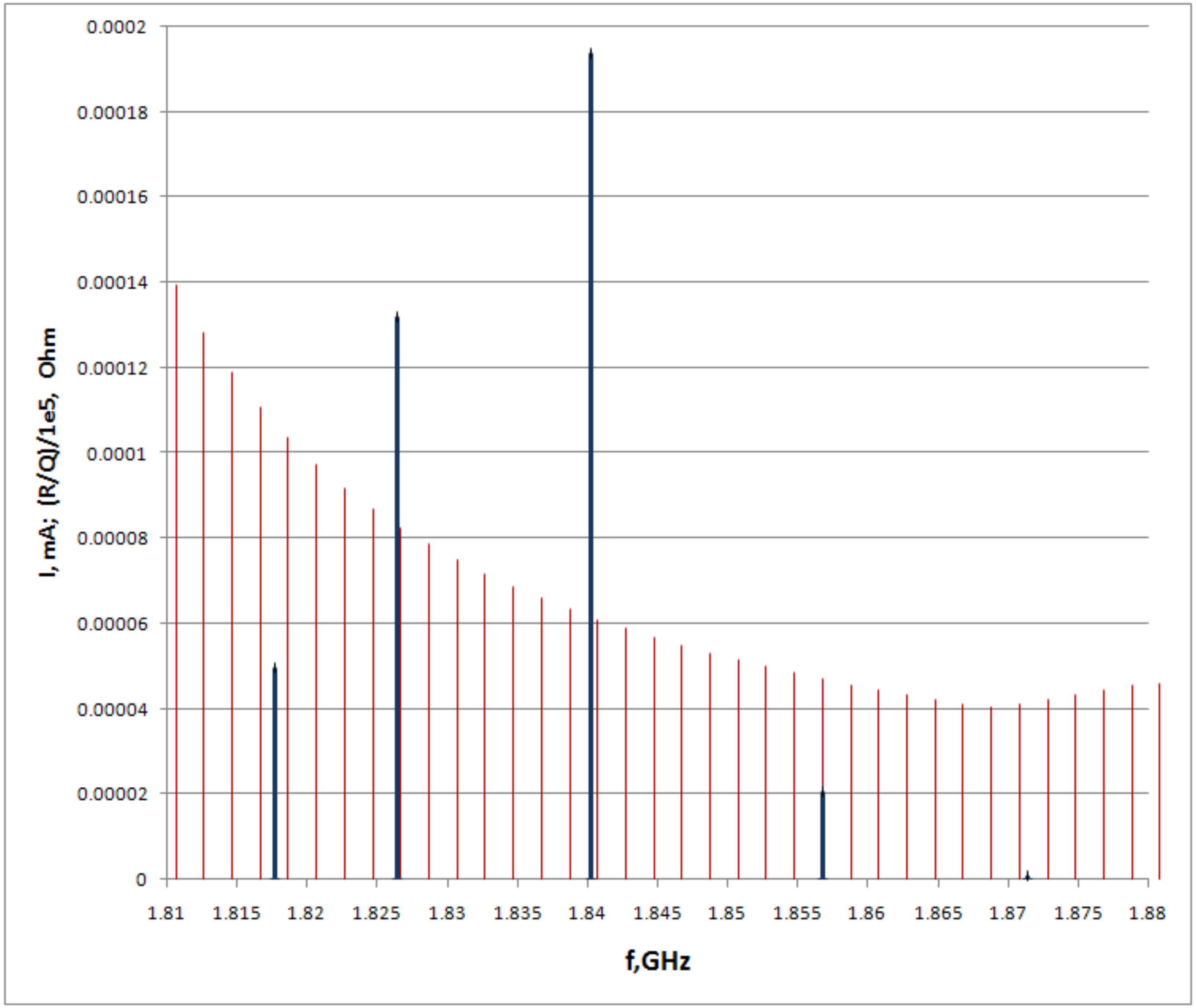
- Mode frequencies are located far off the lines of beam spectrum; nearest line of beam spectrum has current < 10 uA

3d Passband



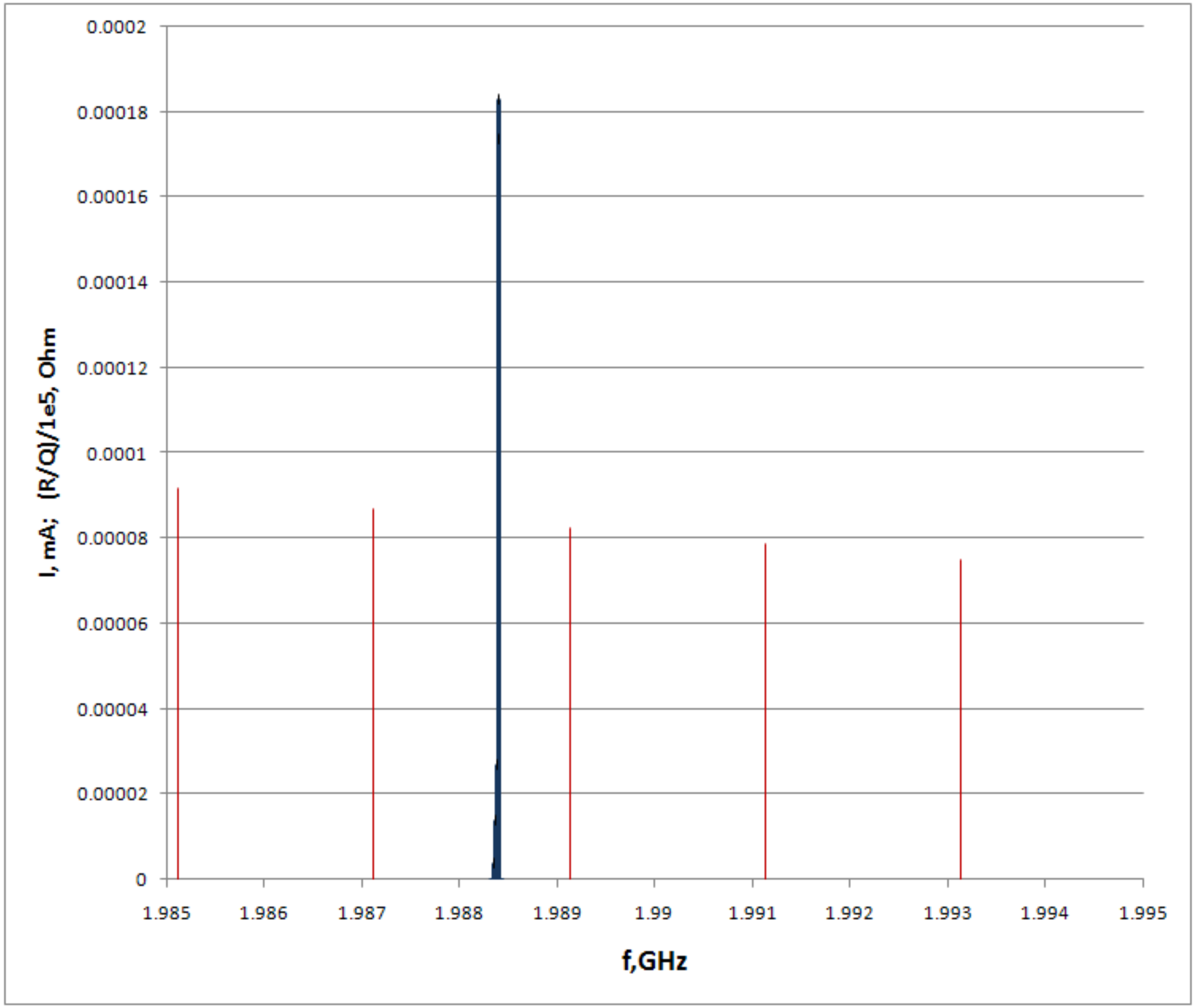
- Mode frequencies are located far off the lines of beam spectrum; nearest line of beam spectrum has current < 10 uA

4th Passband



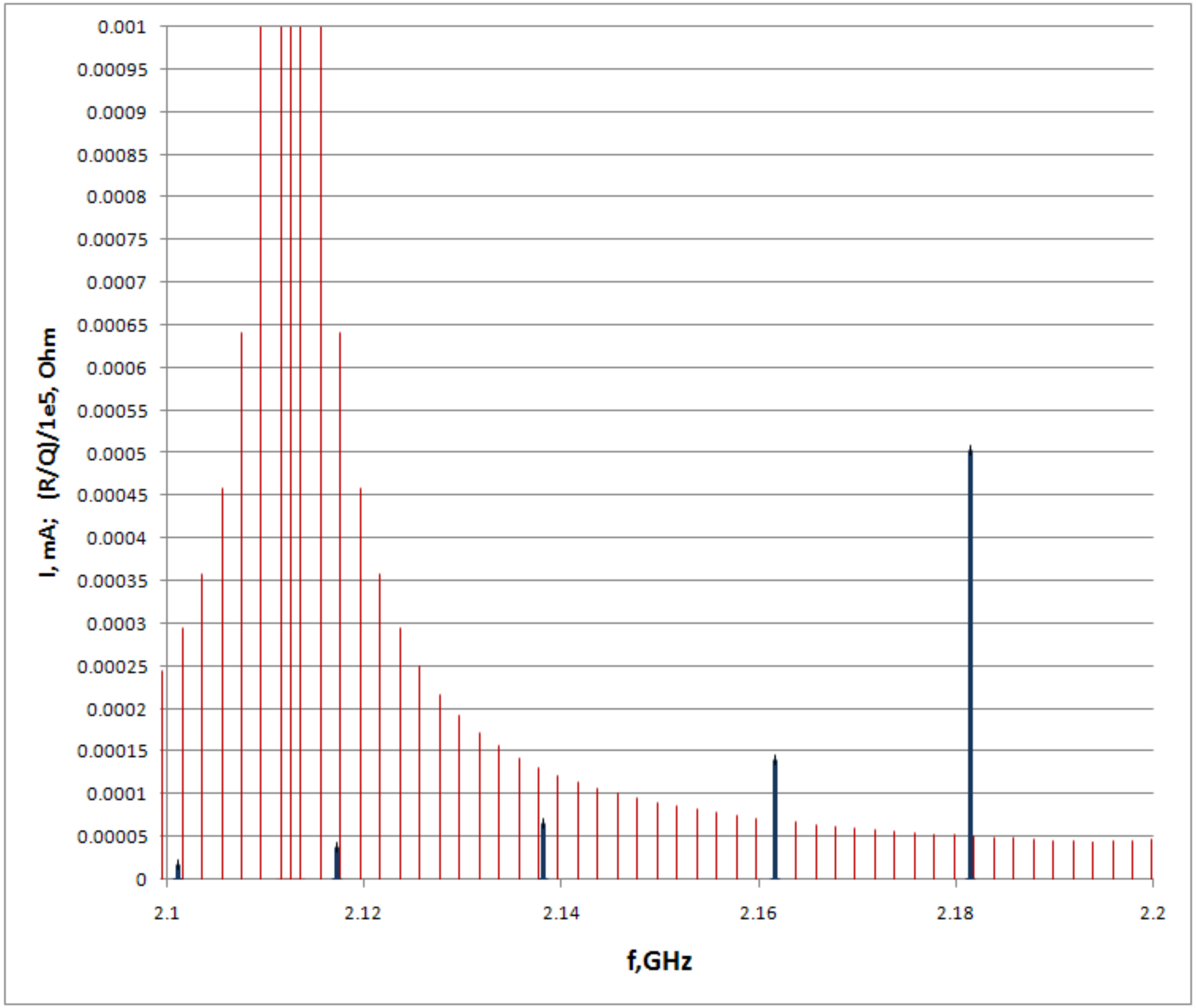
- Mode frequencies are located far off the lines of beam spectrum; nearest line of beam spectrum has current < 10 uA

5th Passband



- Mode frequencies are located far off the lines of beam spectrum; nearest line of beam spectrum has current < 10 uA

6th Passband



- Mode frequencies are located far off the lines of beam spectrum; nearest line of beam spectrum has current < 10 uA

Resonance Excitation Of Monopole HOMs

- Longitudinal beam emittance (ε_Z=1.6 keV*ns) should not increase due to interaction with monopole modes
- If U_{HOM} is average gain caused by HOM, σ_t is bunch length, then $U_{HOM}\,\sigma_t << \varepsilon_Z$
- For high-Q resonances ($\delta f/f >> 1/Q$, $\tilde{I}$ is beam spectrum line amplitude):

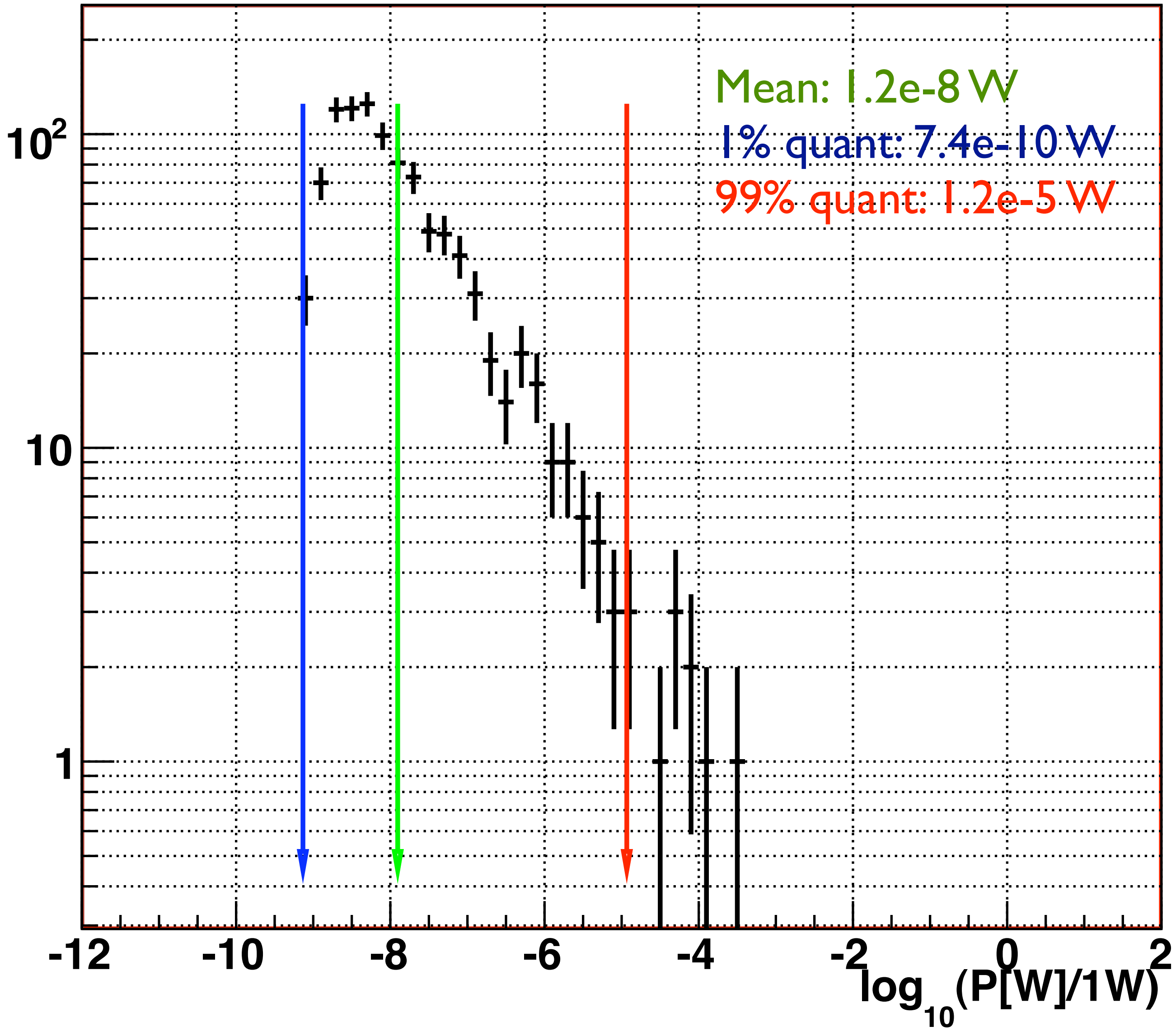
$$U_{\mathrm{HOM}} \approx \frac{\tilde{I}(R/Q)}{4\sqrt{2}\delta f/f},\ \delta f \gg f\frac{\tilde{I}(R/Q)\sigma_t}{4\sqrt{2}\varepsilon_Z}$$

- For example, for beam line with frequency f = 1395.2 MHz, $\tilde{I}$ = 5 uA, (R/Q) = 7 Ohm, and σ_t = 7.7 ps (1.8 deg), δf >> 0.04 Hz
- Other example: beam line with frequency f = 1241 MHz, $\tilde{I}$ = 5 uA, (R/Q) = 130 Ohm, δf >> 0.7 Hz
- Resonance excitation of monopole HOMs does not seem to be a problem

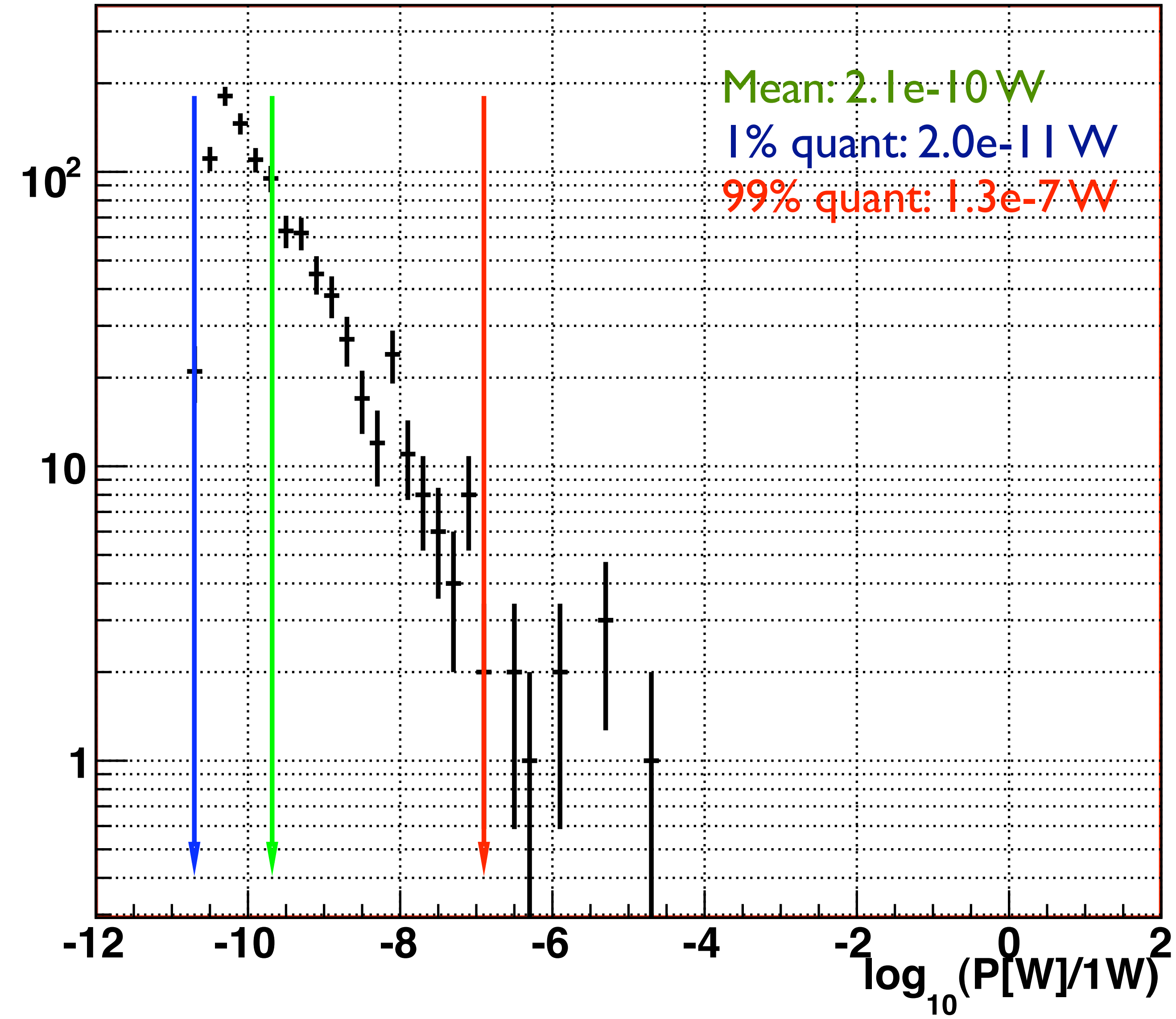
Resonance Excitation of Monopole HOMs

- Power loss in cavity walls, non-propagating monopole HOMs (f<2.3GHz)
  - Distribution of losses is due to spread of HOM frequencies (1 MHz R.M.S.)

Project X beam structure



Muon Collider beam structure



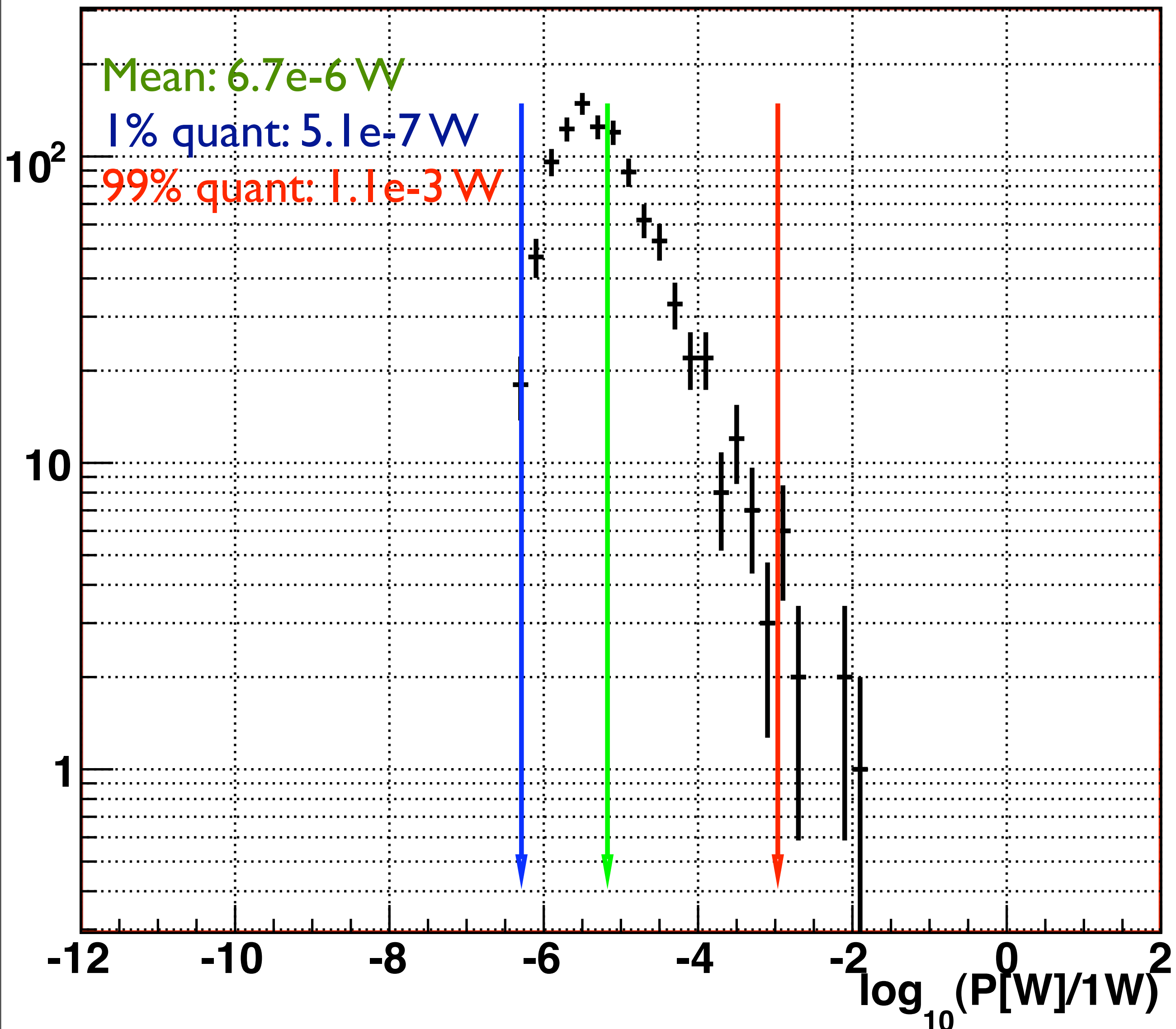
Resonance Excitation of Monopole HOMs

- Power loss in cavity walls, propagating monopole HOMs
- Beam pipe (r=5 cm) cut-off frequency: f = 2.3GHz
  - Most of HOMs w/ frequency above cut-off escape from cavities
  - Some of them may become trapped in cavities
    - reflection and interference with HOMs from adjacent cavities
- Use *VERY* conservative estimation of power loss upper limit:
  - Simulate cavity with beam pipe of length L (= 10-40 cm) on both ends
  - Consider that *all* HOMs w/ frequency above cut-off are trapped in cavities
  - Use maximum values of (R/Q) w.r.t. beam pipe length L and particle velocity
- Justify this approach by results
  - If this method shows that losses are still small, no need to worry about them

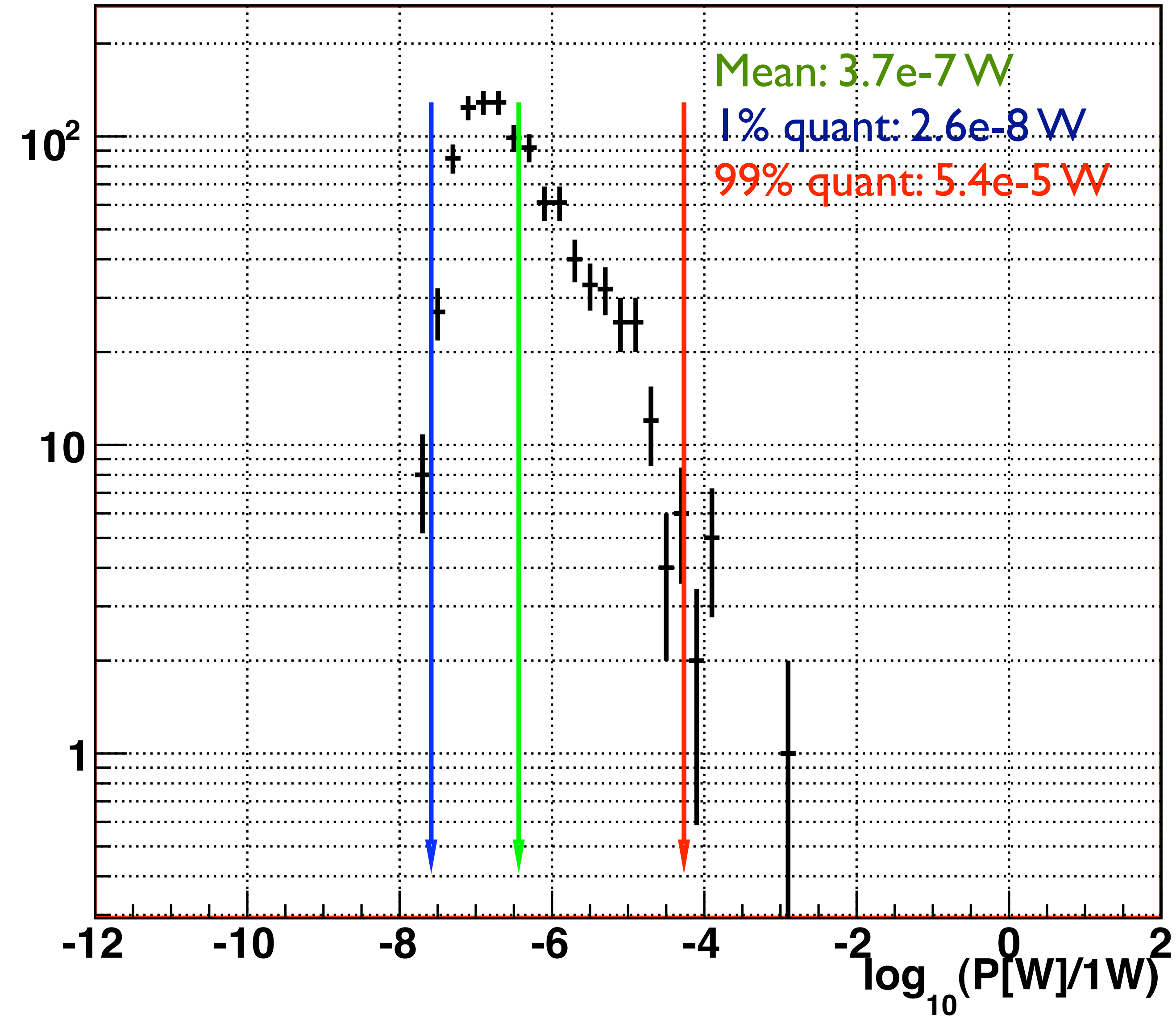
Resonance Excitation of Monopole HOMs

- Power loss in cavity walls, propagating monopole HOMs (f>2.3GHz)

Project X beam structure



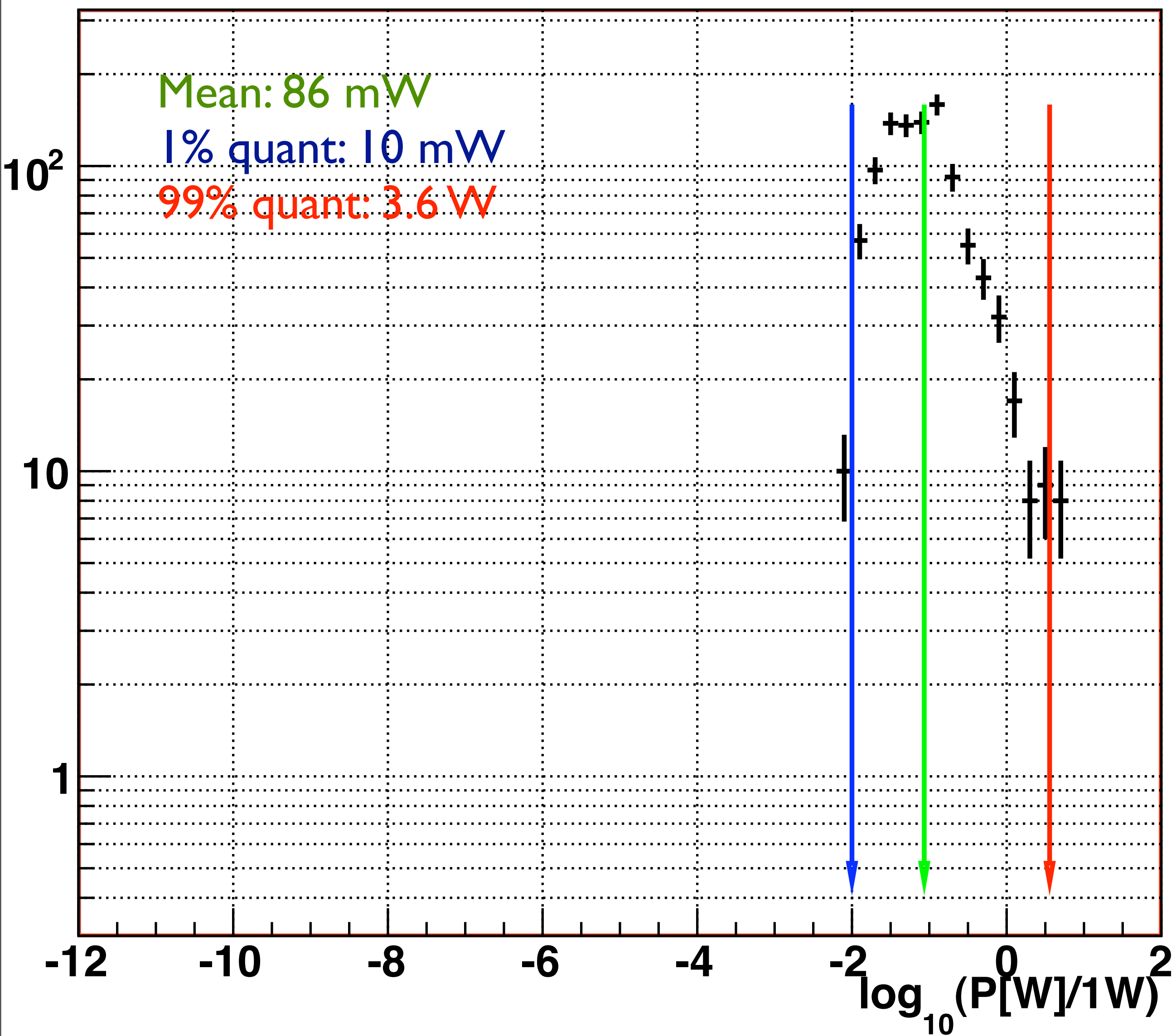
Muon Collider beam structure



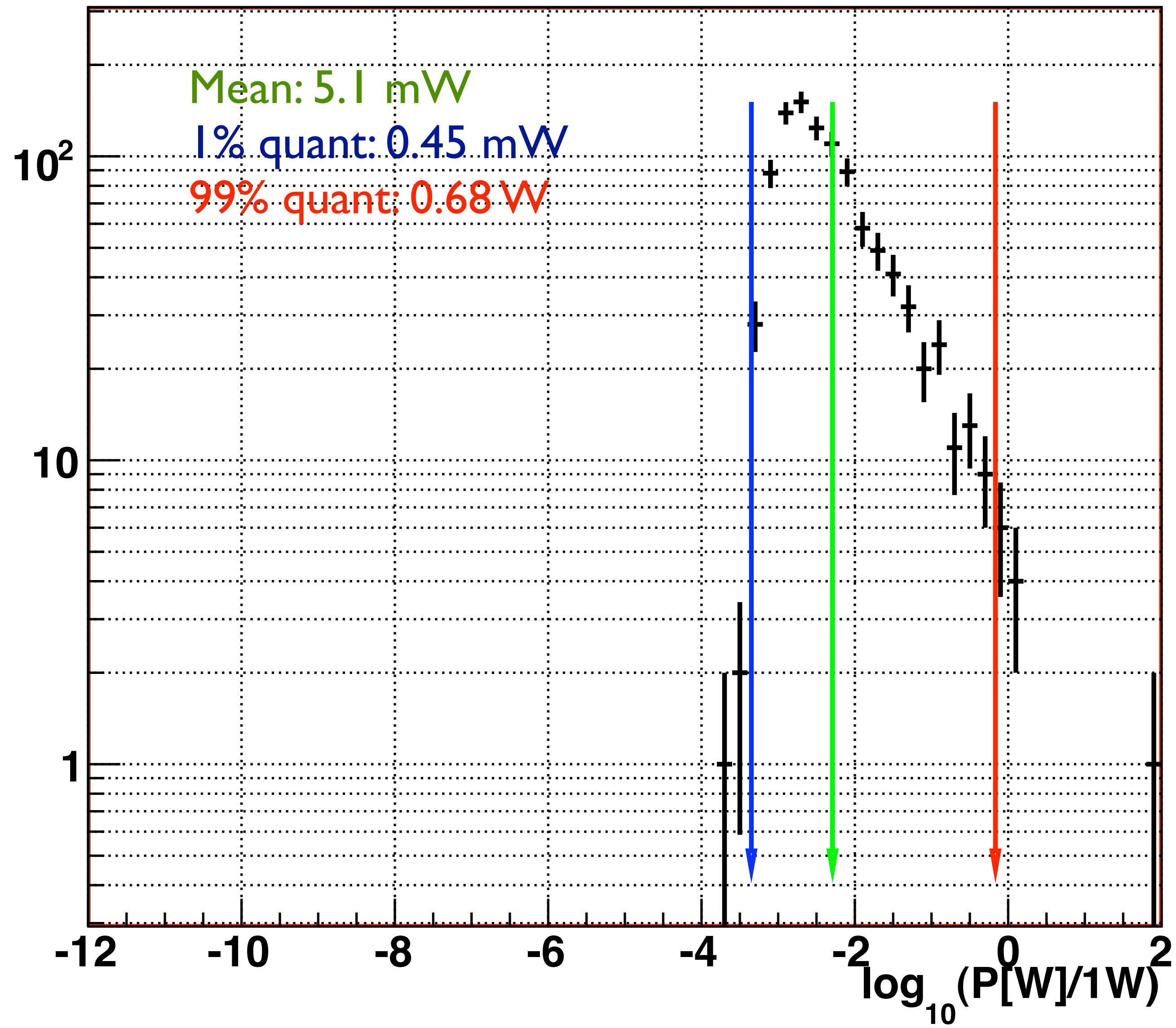
Resonance Excitation of Monopole HOMs

- Power loss in bellows, propagating monopole HOMs (f>2.3GHz)

Project X beam structure



Muon Collider beam structure

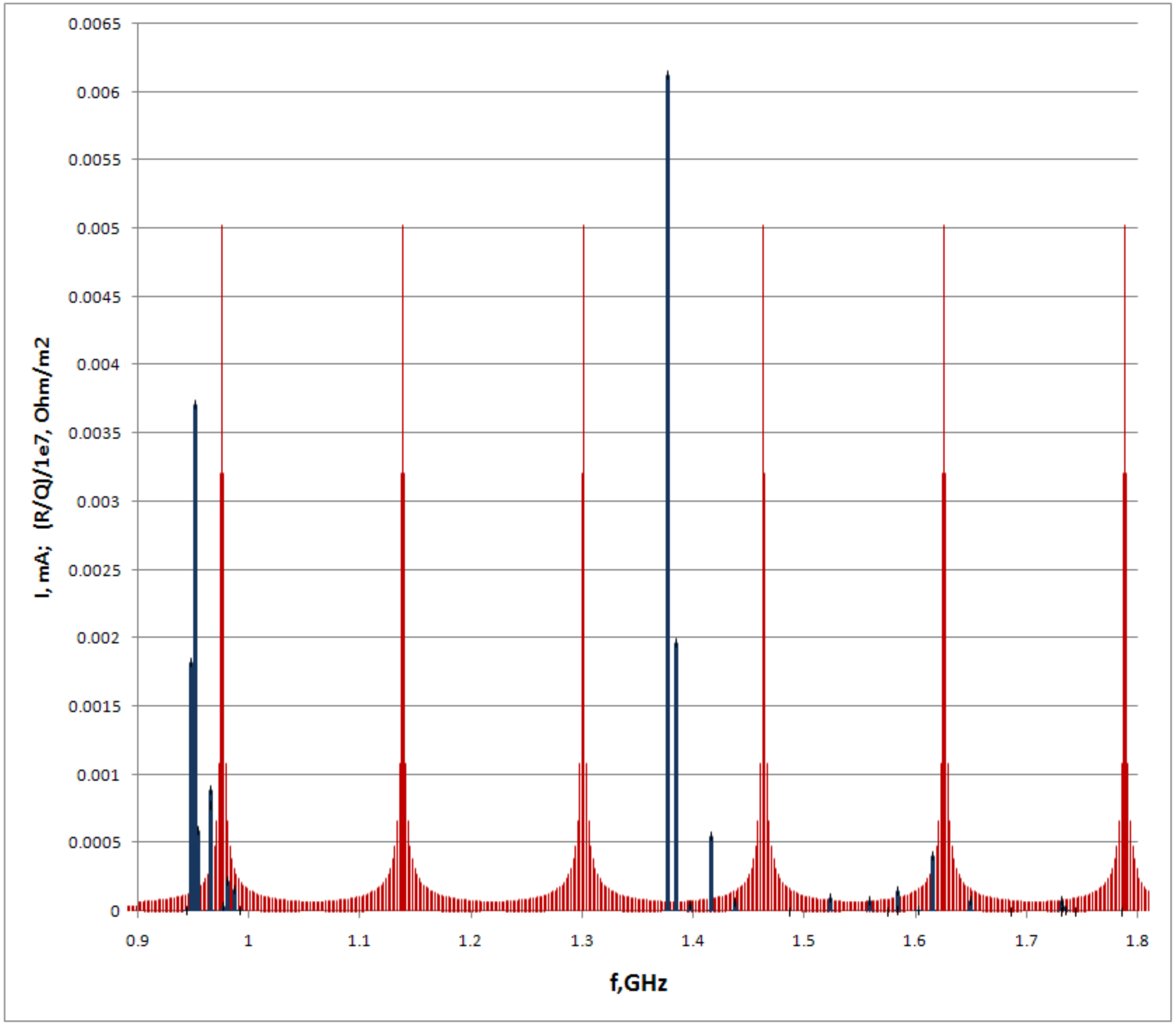


Resonance Excitation of Monopole HOMs: Summary

Power Loss, W	Project X beam structure			Muon Collider beam structure		
	Cav. non-prop. HOMS	Cav. prop. HOMs	Bellows	Cav. non-prop. HOMS	Cav. prop. HOMs	Bellows
Mean	1.20E-08	6.70E-06	0.086	2.10E-10	3.70E-07	5.10E-03
1% quantile	7.40E-10	5.10E-07	0.010	2.00E-11	2.60E-08	4.50E-04
99% quantile	1.20E-05	1.10E-03	3.6	1.30E-07	5.40E-05	0.68

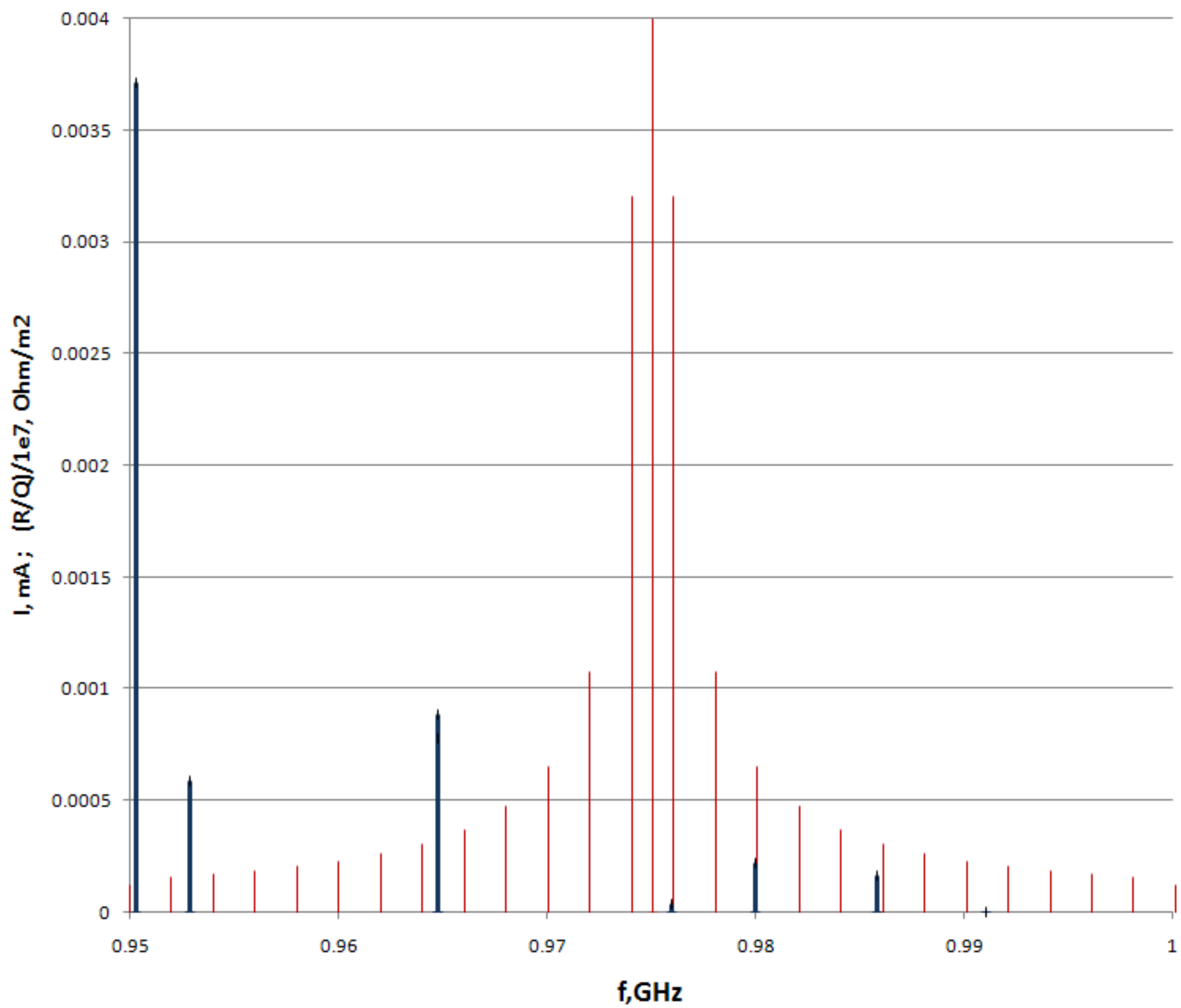
- Muon Collider beam power loss due to resonance excitation of monopole HOMs in HE 650 MHz cavities is a small fraction compared to the power loss of the standard Project X beam structure

Beam Spectrum And Dipole HOMs



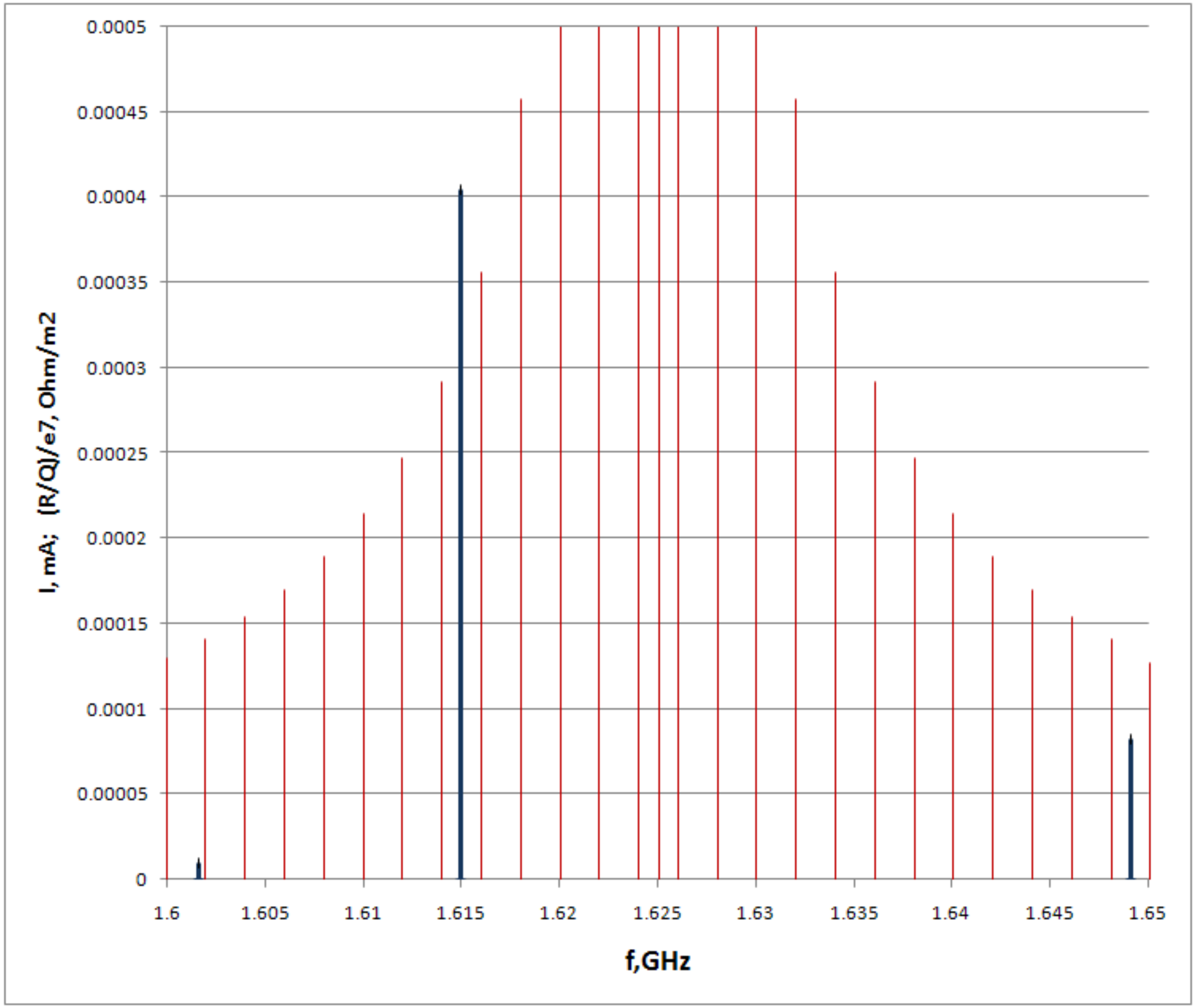
- All strong resonances are far from the main beam spectrum lines

Beam Spectrum And Dipole HOMs At 975 MHz



- Mode with the frequency of 950 MHz has impedance of 37 kOhm/m^2, while the nearest beam spectrum line is 0.2 mA

Beam Spectrum And Dipole HOMs At 1625 MHz



- Mode with the frequency of 1615 MHz has impedance of 4 kOhm/m^2, while the nearest beam spectrum line is 0.35 mA

Resonance Excitation Of Dipole HOMs

- Dipole modes should not increase the beam transverse emittance (ε=2.5e-7/$\beta\gamma$ m)

- Transverse kick caused by the HOMs ($k=2\pi/\lambda$)

$$U_{\text{kick}} \approx \frac{f}{4\delta f}\left(\frac{x_0}{k}\right)\tilde{I}(R/Q)_1 \,,\, \delta f/f \gg 1/Q$$

- Emittance increase (β_f is beta-function at the cavity)

$$\delta\varepsilon \approx \Delta x' \sigma_x = \frac{U_{\text{kick}}}{\sqrt{2}p_{||}c}\sqrt{\varepsilon\beta_f}$$

- Condition of small increase of emittance ($\delta\varepsilon \ll \varepsilon$, U_0 is proton rest energy)

$$\delta f \gg \frac{cx_0\tilde{I}(R/Q)_1}{8\sqrt{2}\pi\beta\gamma U_0\sqrt{\varepsilon/\beta_f}}$$

- For example, for mode f=950 MHz, $(R/Q)_1$=37 kOhm/m^2, proton energy 500 MeV, β_f=15m, beam spectrum line current 2 mA, x_0=1 mm one has: δf >> 5 Hz

- Not a problem!

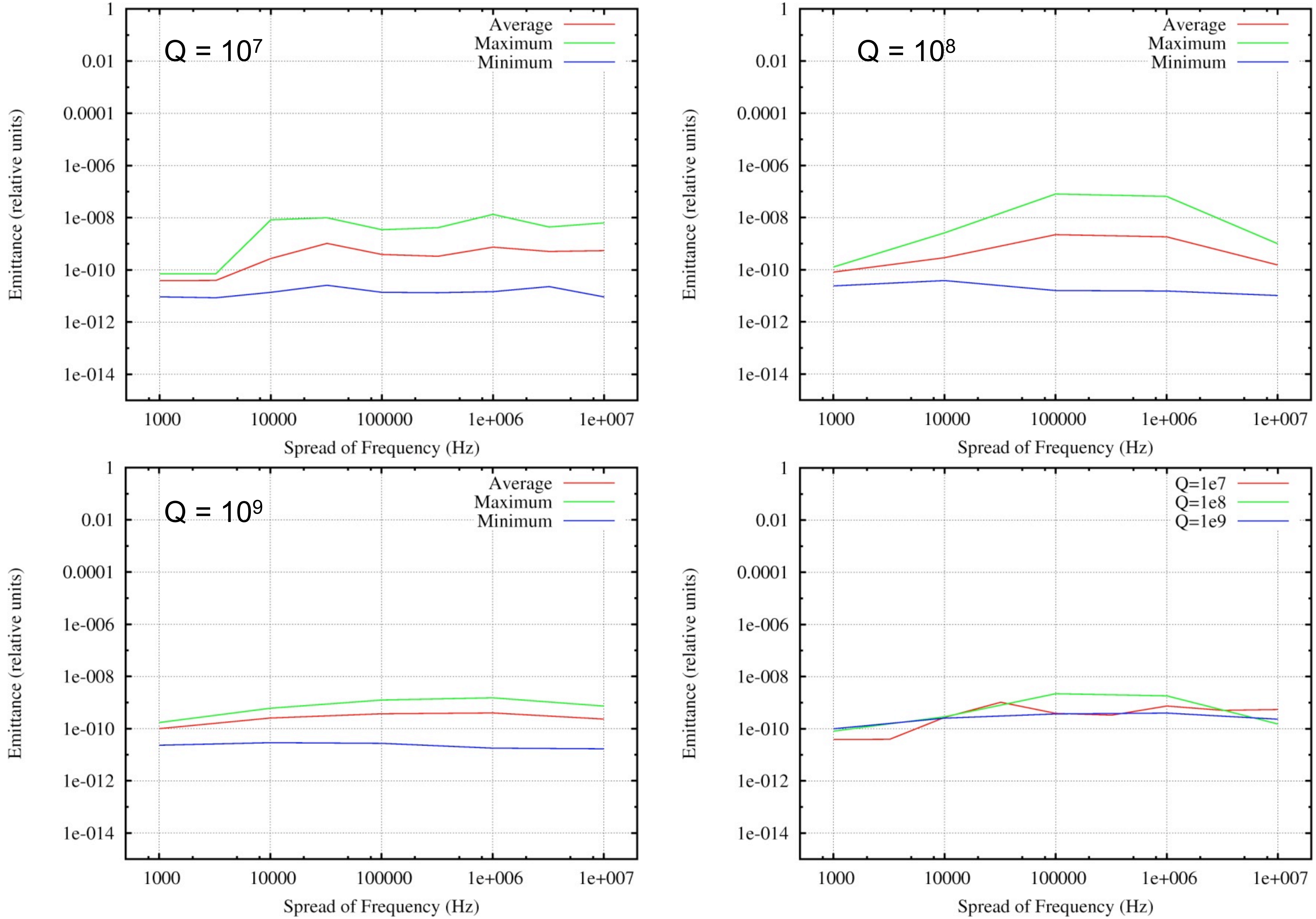
Collective Effects

- Beam break-up (BBU), transverse
- "Klystron-type", longitudinal

- Why collective effects may not be an issue
  - No feedback as in CEBAF
  - Different cavity types with different frequencies and different HOM spectrum
  - HOMs frequency spread in each cavity type due to manufacturing tolerances
  - HOMs (R/Q) dependence on velocity
  - Relatively small beam current
- Simulation shows that relative increase in both transverse and longitudinal emittances is very small and we have safety margin of few orders of magnitude

Collective Effects: Transverse Emittance

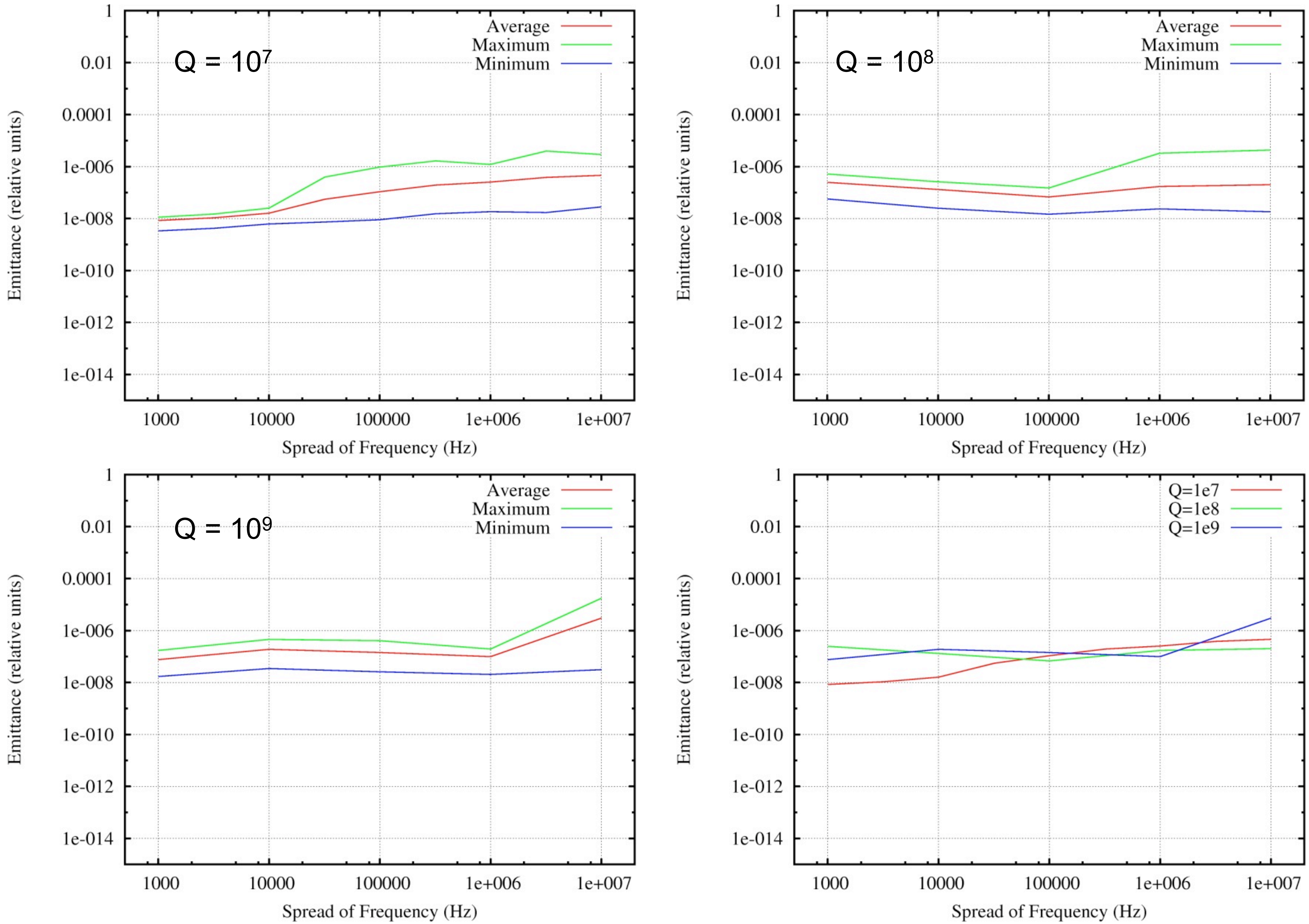
- “Realistic” linac: transverse emittance dilution vs δf (see TD-11-008)



- No noticeable effect

Collective Effects: Longitudinal Emittance

- “Klystron-type” instability: longitudinal emittance dilution vs δf



- No noticeable effect

Summary

- We studied mode of operation of Project X linac as a driver for Muon Collider with 15 Hz pulses of 6.7 ms with 50% DF and average current 5 mA (peak current 10 mA)
- We considered effects of incoherent losses, resonance excitation of monopole and dipole HOMs and collective effects in HE 650 MHz section of Project X linac
- We make a conclusion that these effects are small and we should be able to operate Project X linac as a driver for Muon Collider with specified beam parameters